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Theoretical and experimental investigation of biomass gasification process in a fixed bed gasifier

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ABSTRACT

This investigation concerns the process of air biomass gasification in a fixed bed gasifier. Theoretical equilibrium calculations and experimental investigation of the composition of syngas were carried out and compared with findings of other researchers. The influence of excess air ratio (λ) and parameters of biomass on the composition of syngas were investigated. A theoretical model is proposed, based on the equilibrium and thermodynamic balance of the gasification zone.

The experimental investigation was carried out at a setup that consists of a gasifier connected by a pipe with a water boiler fired with coal (50 kWth). Syngas obtained in the gasifier is supplied into the coal firing zone of the boiler, and co-combusted with coal. The moisture content in biomass and excess air ratio of the gasification process are crucial parameters, determining the composition of syngas. Another important parameter is the kind of applied biomass. Despite similar compositions and dimensions of the two investigated feedstocks (wood pellets and oats husk pellets), compositions of syngas obtained in the case of these fuels were different. On the basis of tests it may be stated that oats husk pellets are not a suitable fuel for the purpose of gasification.

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1. Introduction

Woody biomass residues may be converted into a combustible gas mainly composed of H_2, CO, CO_2, CH_4 and higher hydrocarbons by their thermal decomposition, in order to obtain a valuable gaseous fuel which may be used for heating or power generation. In the gasification process, biomass is decomposed into volatile compounds, char and tars, but yields of these products depend on the type of the gasifier. A review of the gasification technologies, concerning feedstock properties and types of gasifiers presented by McKendry [1], confirmed that updraft gasification is a very simple and reliable technology and is suitable for wet biomass conversion. Updraft gasifiers can effectively use biomass feedstock of differing sizes and moisture content. The major drawback of the updraft gasification process is the high amount of tars, resulting from the process, but this problem is of no importance if the syngas is immediately combusted in a boiler. Syngas with a low calorific value may be used in small scale power generation systems. The amount of tar produced in this process, may be an advantage in the case of immediate combustion of the obtained syngas in a stoker boiler, because of its high heating value.

In the updraft fixed bed gasifier the biomass is fed at the top of the reactor and moves in the opposite direction to gas flow, passing through drying, pyrolysis, reduction and combustion zones. The air intake is at the bottom, below the grate, and syngas leaves at the top. At the bottom of the reactor the char is combusted, liberating H_2O and CO_2 and reducing the O_2 concentration. Hot gases move upwards through the bed above, where they are reduced to H_2 and CO. Reduced gases move up the bed and pyrolyse the biomass, then they dry the incoming biomass liberating H_2O and leave the reactor at a relatively low (in comparison to downdraft gasifier) temperature.

This study explores the potential of the syngas obtained by air biomass gasification in an autothermal gasifier in order to determine the utility of gasification process for small scale co-combustion systems.

2. Theoretical calculations

2.1. Model description

Theoretical knowledge of the composition of syngas provides valuable information about the optimal parameters of the gasification process, in order to obtain as much as possible calorific gaseous fuel. As a first assumption of the syngas composition, a thermodynamic analysis is commonly used, which is based on

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Table 1
Proximate and ultimate analyses of the applied fuels (wt., dry basis).

	Wood pellets	Rape straw	Corn straw	Sunflower stem
Proximate analysis				
LHV kJ/kg	19190	19033	16918	15663
Ash %	1.07	6.93	7.16	13.15
Volatile matter %	77.70	75.80	76.8	72.70
Ultimate analysis				
C %	52.01	47.10	45.70	42.50
H %	5.81	5.90	5.30	5.10
O %	40.82	39.26	41.13	38.10
N %	0.28	0.80	0.70	1.10
S %	0.01	0.01	0.01	0.01

equilibrium in the gasification zone. Equilibrium equations, elements and energy balances were applied to predict the composition of syngas and its calorific value. Parameters taken into consideration were the biomass composition, initial moisture content in raw biomass, the excess air ratio in the gasification zone, gasification temperature and external heat losses from the reactor. The moisture content in raw biomass was assumed to be within the range of 0–40% (wt.) and the excess air ratio was assumed to vary within the range of 0.3–0.6. External heat losses were within the range of 0–10% of the energy put into the reactor. Calculations of the syngas composition concerned 4 cases of gasified biomass: wood pellets, rape straw, corn straw and sunflower stems – calculations may be carried out for any biomass fuel, for which proximate and ultimate analyses are known. Proximate and ultimate analyses of investigated feedstock are presented in Table 1.

In theoretical investigations, it has been estimated, that the residence time of the reactants in the reactor is long enough to achieve equilibrium. Chemical reactions in the reduction zone of the gasifier taken into consideration in the model were the formation of methane and the water gas shift reaction. For these reactions the equilibrium constants were defined, and after applying the Gibbs–Helmholtz equation, integrating and transformations, the final formulas for equilibrium constants for these reactions were determined as a function of the temperature. The set of equations solved for the purpose of calculating the syngas composition consists of six equations: three elements balances (C, H, O), two equilibrium constant equations and one energy balance equation. For the purpose of multi-variant calculations a computer code was developed by means of Engineering Equation Solver.

A more detailed analysis of this theoretical approach was presented in an earlier reference paper [2]. This paper only quotes the main assumptions and results obtained in theoretical investigations. More emphasis is put on the experimental part.

2.2. Results of the investigation

As a result of computational investigations, the composition of syngas was obtained, assuming that the main components are CO, CO_2, H_2O, H_2, N_2 and CH_4. The influence of the crucial parameters of the gasification process on the syngas composition is presented in Figs. 1–4. Fig. 1 presents the variation of composition of syngas as a function of the excess air ratio in the case of mixed wood gasification with the initial moisture content of 10%.

Within the entire investigated range of λ, the molar fraction of CH_4 is very low (max. 3%) and it is decreasing with the increment of λ. The molar fraction of H_2 in the obtained gas is decreasing with the increment of the excess air ratio from 20% to 6.5%, while CO_2 is slightly decreasing from 8.9 to 8.5% for $\lambda = 0.38$ and then increasing to 11.3%. The molar fraction of CO decreases from 25.9% to 16.6%. The amount of N_2 increases continuously with the increment of λ, as has been expected. More detailed investigations of different biomass feedstock showed that a maximum value of molar fraction of CO and a minimal value of molar fraction of CO_2 in the syngas can be distinguished. The lower heating value (LHV) of the obtained syngas is in the range of 2800–6100 kJ/Nm^3 and the decrement is caused by the increasing of the molar fraction of N_2 and the decreasing of the molar fractions of combustible species in the syngas.

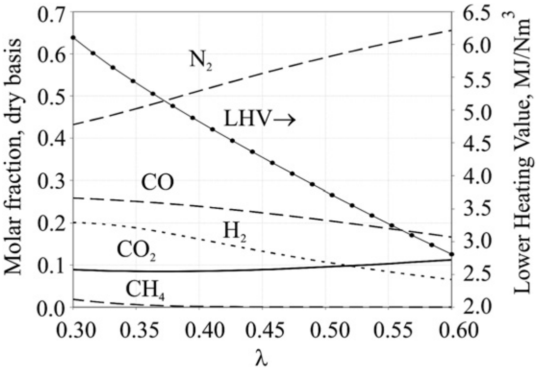


Fig. 1. Variation of the composition of syngas with the excess air ratio.

Fig. 2 presents the dependence of the molar composition of the obtained syngas on the varying moisture content in raw biomass in the case of wood pellets gasification with an excess air ratio of $\lambda = 0.4$.

It can be seen that the increment of the moisture content increases the molar fraction of CH_4, which can be explained by the Le Chatelier–Braun Principle. With the increment of the moisture content, the molar fraction of CO is decreasing from 23.9% to 10.9%, while the amount of CO_2 is increasing from 8.5% to 18%. The molar fraction of H_2 is increasing with the increment of the moisture content from 16% to 20.5%.

Figs. 3 and 4 present a comparison of the obtained results in the case of all investigated feedstocks for the assumed initial moisture content in biomass equal to 10%. These figures show the variation of the main combustible components of the syngas.

As can be seen in Fig. 3, the increment of the excess air ratio at a constant value of the initial moisture content in raw biomass causes a decrement of the H_2 content in the syngas. The highest molar fraction of H_2 was obtained in the case of rape straw gasification and the least one by the gasification of wood pellets. Fig. 4 presents the dependence of the molar fraction of CO and CO_2 against the excess air ratio. The molar fraction of CO varies from

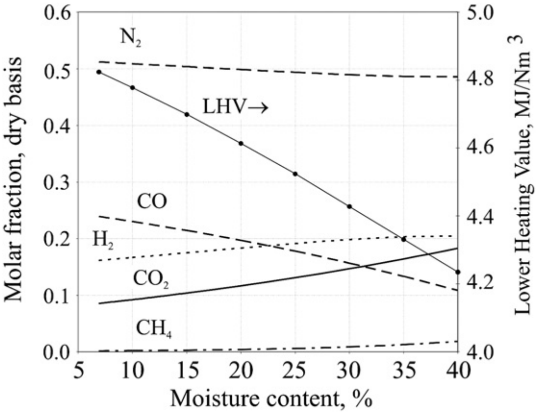


Fig. 2. Influence of the moisture content in raw biomass on the syngas composition.

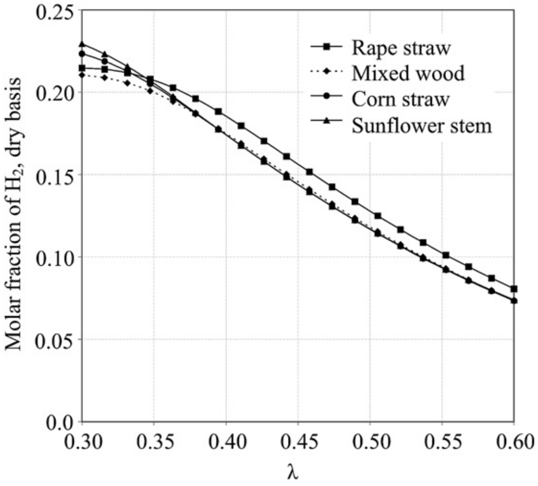


Fig. 3. The molar fraction of H_2 as a function of the excess air ratio.

about 22% to 15%. Maximum concentration of CO can be distinguished for $\lambda \approx 0.3$ and the highest values are noticed in the case of corn straw. In the same diagram a minimum value of the molar fraction of CO_2 can be seen, which is observed for $\lambda = 0.4–0.45$. The highest percentage of CO_2 is associated with sunflower stems followed by corn straw, rape straw and wood pellets.

Theoretical results obtained with our model were compared with different theoretical models ([3,4]) and they are in good agreement. Comparison concerned the case of mixed wood gasification with an initial moisture content 10% and for temperature in the gasification zone $t_{gasif} = 800\,°C$. Results are shown in the Fig. 5. The model can be applied to predict the syngas composition before the gasifier is to be designed in order to predict the parameters of the gasifier and to optimize its operating conditions.

3. Experimental study

For the purpose of experimental investigations a laboratory system was designed and built. A schematic diagram of the system is presented in Fig. 6 and scheme of the syngas generator is presented in Fig. 7. The gasification chamber was constructed from four cylindrical segments lined with refractory rings, with an internal diameter of 0.25 m and total height of 0.60 m. The maximum capacity was 20 kg of wood pellets. The syngas generator was placed on a scale to measure the mass decrement of gasified fuel. Temperature of the gasifier interior was measured by six N-type and K-type thermocouples located along the gasifier vertical axis at different heights. Additionally, the temperature of the syngas at the outlet of the gasifier and the temperature of the exhaust gases from the boiler were also measured. The air flow rate supplied into the gasifier was measured by a flow meter. At the outlet of the gasifier there was a syngas sampling point, where the syngas sample was collected and cleaned by a system of filters and then supplied to CO and H_2 analysers. Molar fractions of these two combustible species were measured on-line at the experimental stand and for a few specified experimental points the composition of syngas was investigated by chromatographic analysis. The gasifier is connected by a pipe with a water boiler, thus the syngas obtained in the gasification process is supplied into the firing zone of the boiler and co-combusted with coal. Biomass is fed into the reactor from the top, while air is supplied by a blower from the bottom. The biomass feedstock moves in a countercurrent direction to the gas flow and passes through the drying, pyrolysis, reduction and combustion zones. In the drying zone the moisture is evaporated. In the pyrolysis zone the biomass is thermally decomposed to volatiles and solid char. And in the reduction zone carbon is converted, and CO and H_2 are produced as the main components of the syngas. In the combustion zone the remaining char is combusted providing heat for endothermic reactions in the upper zones. The gasifier was initially designed to ensure about 10% of the nominal heat power of the boiler, which is 50 kW_{th}.

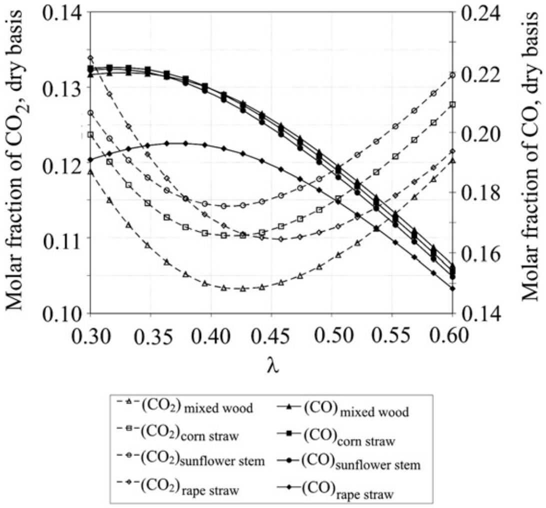


Fig. 4. Molar fractions of CO and CO_2 as a function of the excess air ratio.

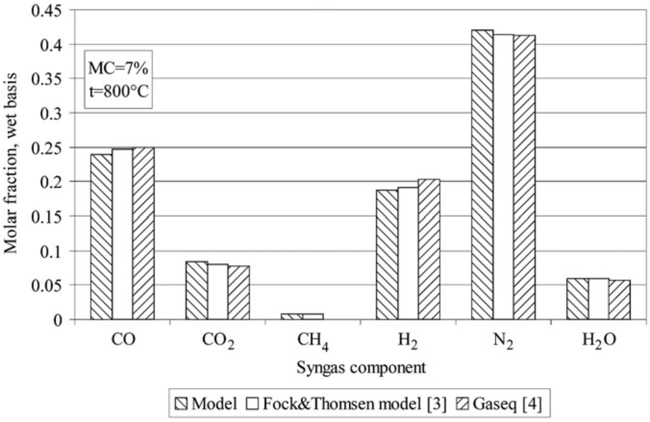
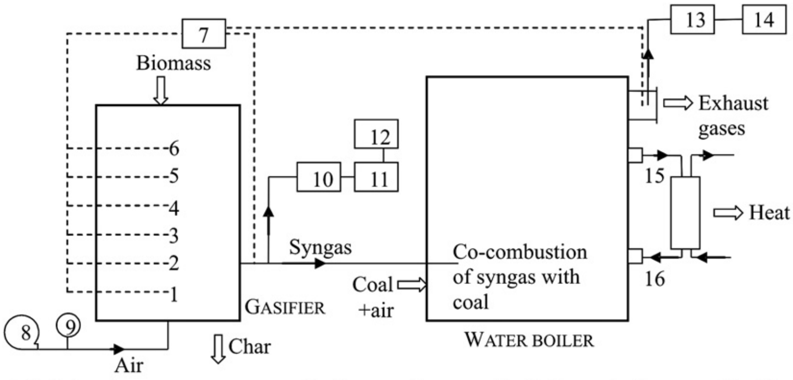


Fig. 5. Comparison of the results with a different models ([3,4]).

3.1. *Experimental procedure*

Two kinds of biomass were gasified: wood pellets and oats husk pellets. Both of these fuels are of cylindrical shape, with a diameter of 6 mm and a length of 10–30 mm. Proximate and ultimate analyses (weight basis, as received) of these fuels are quoted in Table 2.

The experimental procedure starts with firing up the boiler. When the parameters of the boiler reached a steady state (heat power), the gasifier was fired up. The blower was switched on and biomass was put in through the port in the upper part of the gasifier, and ignited through a port in the bottom. After approximately 2 h the gasifier was heated and the experimental measurements started. The scale, on which the gasifier was placed, was turned on and the gasifier was filled with a fresh quantity of biomass. The air flow rate to the gasifier was adjusted to ensure the



1-6 – Points of temperature measurement, 7 – Data recording system, 8 – Air blower, 9 – Flow meter, 10 – Cleaning & cooling system, 11 – Syngas composition analyzer, 12 – Gas sample, 13 – Cleaning & cooling system, 14 – Exhaust gases analyzer, 15 – Hot water, 16 – Feedwater

Fig. 6. Schematic diagram of the experimental system.

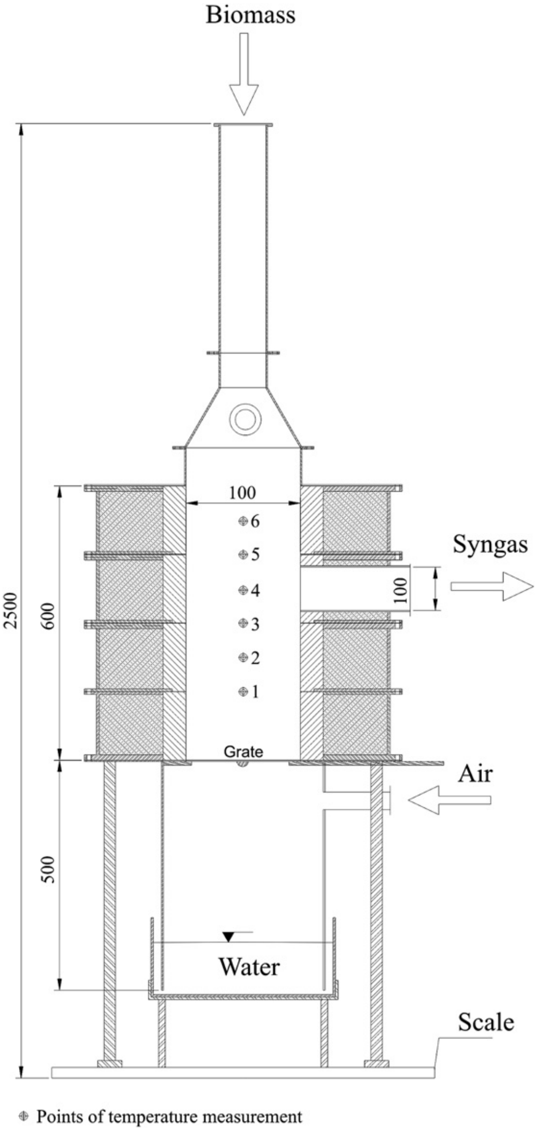


Fig. 7. Schematic diagram of the syngas generator.

excess air ratio at the specified level. Once syngas production began, measurements of key variables started. The molar fractions (dry basis) of CO and H_2 in the syngas, and the composition of exhaust gases from the boiler were measured on-line by analysers. The increment of heat power in the boiler was measured by an electronic heat meter.

3.2. Temperature distribution in the gasifier

The temperature profile was measured by a set of thermocouples situated at different heights in the gasifier: the temperature t_1 is measured at 150 mm, t_2 at 225 mm, t_3 at 300 mm, t_4 at 375 mm, t_5 at 450 mm, t_6 at 525 mm over the grate. The temperature distribution along the height of the gasifier is shown in Fig. 8, where 1-6 means the number of the thermocouple placed over the grate. The temperature in the gasifier ranged from 1000 °C in the combustion zone to 130 °C in the drying zone. Fig. 8 shows that the temperature in the gasifier decreases along the height from the bottom. It can be seen that the temperatures of the upper parts of the gasifier increase slower and it takes more time to achieve higher temperature level of these zones than in the case of the oxidation zone. The temperature of the oxidation zone varies within the range of 800–1000 °C. It is difficult to distinguish the height and temperature ranges of other zones of the gasification process, but determining these zones was not the objective of this study.

Table 3 presents exemplary operating conditions of the gasifier and the results of the gasification process.

The data presented in Table 3 concern the experimental runs, for which the full analysis of the syngas was investigated. The air to

Table 2
Proximate and ultimate analyses of the investigated feedstock.

	Wood pellets	Oats husk pellets
Moisture content %	7.0	7.0
Lower heating value kJ/kg	17,681	16,319
Proximate analysis		
Fixed carbon %	21.30	22.60
Ash %	1.00	2.60
Volatile matter %	77.70	74.80
Ultimate analysis		
C %	48.41	44.20
H %	5.41	5.49
O %	37.99	39.19
N %	0.26	1.51
S %	0.01	0.08

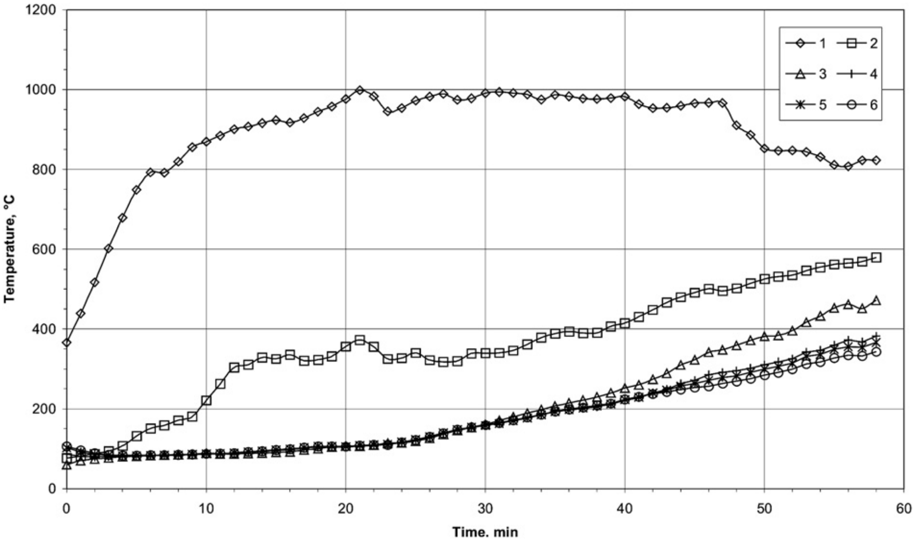


Fig. 8. Typical temperature profile along the height of the gasifier.

fuel ratio is defined as the volumetric flow of dry air, measured by a flow meter, related to the mass flow of fuel supplied into the reactor. Cold Gas Efficiency (CGE) is calculated as the chemical enthalpy of the syngas calculated on the basis of its composition related to the chemical enthalpy of the gasified biomass, while Hot Gas Efficiency (HGE) is the total enthalpy of the syngas related to the chemical enthalpy of the biomass. Results of the experiment for several runs, where H_2 and CO molar fractions were measured on-line at the laboratory stand are presented in Figs. 9–12. CO and H_2 were the most significant combustible syngas species, thus they, and the methane, influence the lower heating value of syngas most.

3.3. Influence of the excess air ratio on the composition of syngas

Fig. 9 presents the results obtained during the gasification of wood pellets concerning two different values of the excess air ratio. In the first case (denoted as 1), the gasification process was carried out with the excess air ratio $\lambda = 0.29$, and the excess air ratio in the second case (denoted as 2) was $\lambda = 0.20$. The case denoted as 2 in Fig. 9 is not presented in the Table 3, because the full syngas composition for this run was not investigated. The initial mass of the fuel was the same in both cases. It took approximately 40 min to obtain steady molar fractions of CO and H_2 in the syngas. The molar fraction of CO is within the range of 23–29%, while the molar fraction of H_2 is within the range of 5–9%. After 140 min, molar fractions of these combustible species were decreasing, entailed by the fuel burnout. The average increment of the molar fraction of CO in the syngas in the first case is higher then in the second case (denoted as 2) by 3–4%. It can be seen that higher amounts of air provided into the gasifier (case 1) cause a higher molar fraction of CO in the syngas. This phenomenon was confirmed by theoretical calculations presented in Fig. 4. At lower values of λ, an increment of the excess air ratio causes the increment of the CO molar fraction until it reaches its maximum, and a further increment decreases the molar fraction of CO.

3.4. Influence of biomass on the composition of syngas

Fig. 10 presents a comparison of the obtained gasification results for two different fuels. Case 1, marked by the solid line, concerns wood pellets gasification and the dotted line presents the results in the case of gasifying oats husk pellets.

The initial mass of the fuels supplied into the reactor were different in both cases and, for that reason, the duration of the gasification process differs in both cases, but the excess air ratio amounted in both cases to $\lambda = 0.27–0.29$. Even though the proximate and ultimate analyses of both investigated fuels are similar (Table 2), a large difference in the molar fraction of CO in the syngas can be distinguished. In the case of wood pellets gasification, the molar fraction of CO was within the range of 15–28%, while in the

Table 3
Syngas composition obtained in the case of wood pellets gasification.

Run No.	Fuel moisture content wt., %	Fuel flow kg/h	Air flow Nm^3/h	Air/Fuel Nm^3/kg	λ	Syngas composition vol., dry basis, %							LHV MJ/Nm^3	CGE %	HGE %	t_{gas} °C
						H_2	O_2	CO	CO_2	CH_4	C_{2+}[a]	N_2				
1	7.0	4.1	5.5	1.34	0.29	7.13	1.44	27.47	6.22	1.88	0.14	54.68	4.99	51.2	55.6	280
2	7.0	6.2	9.6	1.55	0.33	9.30	3.49	21.67	8.97	2.84	0.21	54.22	4.89	58.8	61.6	170
3	7.0	6.4	8.7	1.36	0.28	9.31	1.44	25.12	10.52	2.81	0.23	51.53	5.32	58.8	61.0	150
4	7.0	5.9	6.7	1.13	0.24	10.42	2.08	21.97	12.86	3.25	0.29	49.99	5.24	50.0	51.2	110
5	7.0	5.9	7.4	1.25	0.26	10.87	1.99	22.79	11.65	3.14	0.19	49.60	5.35	56.4	57.7	108
6	16.1	6.0	7.4	1.23	0.29	9.40	2.05	17.59	10.48	1.51	0.16	54.67	3.92	41.9	47.1	300
7	16.0	5.6	6.1	1.09	0.25	8.89	2.60	18.02	12.69	2.53	0.05	55.05	4.18	38.9	41.0	150
8	13.0	5.5	7.9	1.44	0.32	8.37	2.03	16.44	14.29	2.29	0.01	57.98	3.84	42.9	44.8	130
9	7.0	10.0	14.0	1.4	0.29	12.33	2.25	22.16	12.42	3.17	0.16	55.33	5.47	57.9	59.9	145
10	7.0	16.0	19.0	1.19	0.26	9.85	1.08	19.08	16.3	3.95	0.23	47.76	5.39	56.4	59.7	240
11	7.0	12.9	18.9	1.47	0.31	8.79	1.33	25.25	8.94	2.23	0.12	51.71	5.08	60.3	64.9	280
12	7.0	7.1	10.4	1.46	0.31	10.73	1.18	25.02	8.68	2.57	0.12	51.29	5.38	64.3	67.9	220

[a] $C_{2+} = C_2H_6 + C_3H_8$

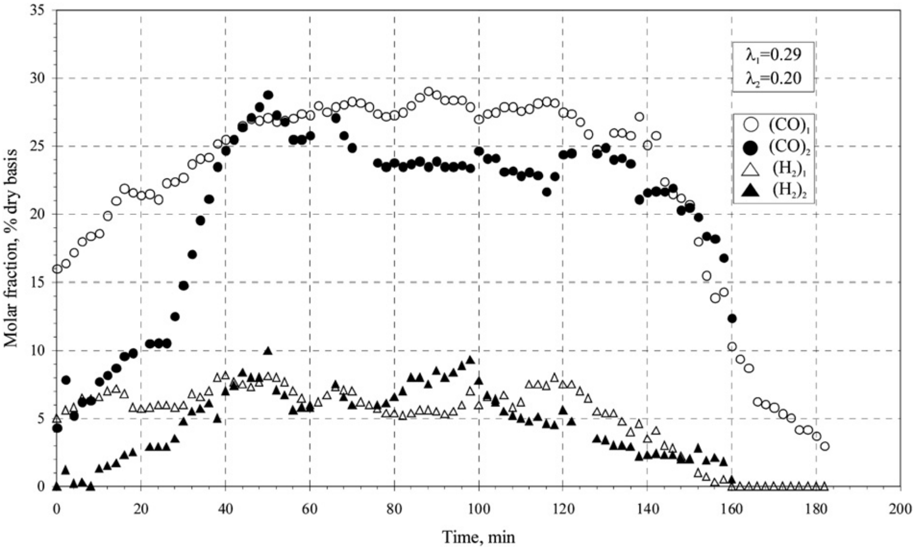


Fig. 9. Variation of molar fractions of CO and H_2 with time.

case of oats husk pellets used as fuel, the molar fraction of CO was equal to 11–16%. All the parameters of the gasification process were the same in both cases and this difference in the molar fractions of CO may be due to the reactivity of the fuel. The molar fractions of H_2 in the syngas were on a similar level in both cases, within the range of 4–8%. The molar fraction of H_2 was higher by 2–3% in the case of wood pellets gasification.

3.5. *Influence of initial moisture content in biomass on the composition of syngas*

The moisture content in the fuel greatly affects the operation parameters of the gasifier and the composition of syngas. The temperature drop inside the gasifier is caused by the heat needed to evaporate the moisture, which influences the quality of the syngas. Thus, the influence of the moisture content in raw biomass was investigated for a few cases: for dried (moisture content: MC = 7%) and humid pellets (MC = 13%, MC = 16%). The results for the case No. 2 and No. 8 (Table 3) are compared in Fig. 11. Both cases were investigated with similar parameters of the gasification process and it is clearly seen that the moisture content in the biomass is not favorable. The main differences in the syngas composition occur, in these cases, between the molar fractions of CO and CO_2 in the syngas. In the case No. 8, the molar fraction of CO in the syngas was lower than in the case No. 2. LHV of the syngas was also lower in the case No. 8 and thus CGE of the gasification process was lower-58.8% for the case No. 2 and 42.9% for the case No. 8.

The data in Table 3 show that the moisture content greatly affects the efficiency of the gasification process. For dry biomass (MC = 7%, wt.), for all investigated cases, CGE exceeded 50%, while in the case of wet biomass gasification the value of CGE dropped to 40%.

3.6. *Influence of the syngas production on parameters of the system*

The gasifier was fired up when the heat power of the boiler was steady on a specified level. The heat power of the boiler was

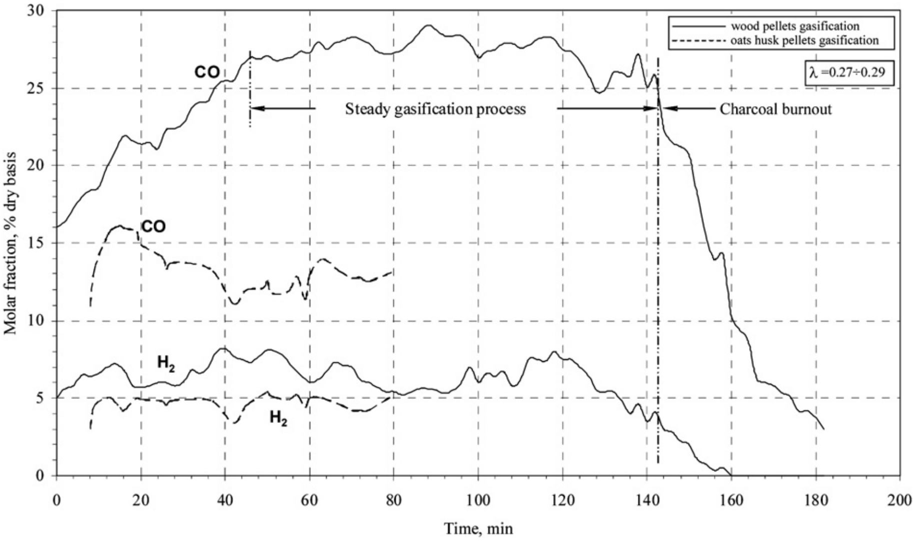


Fig. 10. Comparison of the results in the case of wood pellets and oats husk pellets gasification.

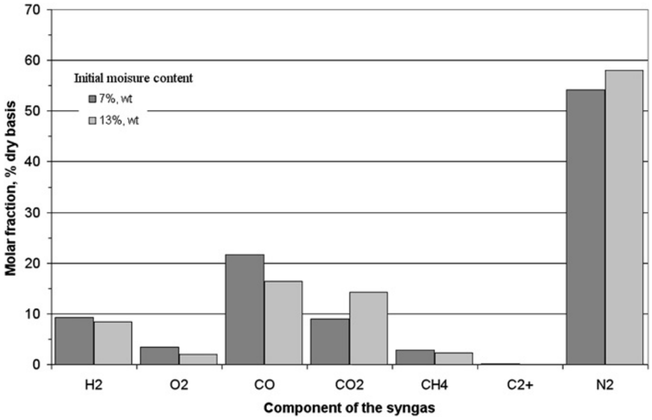


Fig. 11. Comparison of the syngas composition in the case of dry and wet biomass gasification.

measured by a heat meter and recorded once a minute. Fig. 12 presents variations of the heat power of the system with time. In the case presented in the diagram, the heat power of the boiler was adjusted to 25–26 kW and the gasifier was fired up. When the production of syngas started, it was introduced into the boiler and co-combusted with coal; thus the heat power of the gasifier-boiler system started to increase. The maximum increment of the heat power of the system in the case presented in Fig. 12 was 5 kW, which was 19.2% of the preset power of the boiler. The average increment of the heat power was 3 kW, which was 11.5% of the heat power of the boiler.

3.7. Comparison of the results

Results obtained in the experimental investigation were compared with other authors' experimental findings. Table 4 shows a comparison of the experimental dry syngas composition with data presented in [5] and [6], and a good agreement with these data is to be seen.

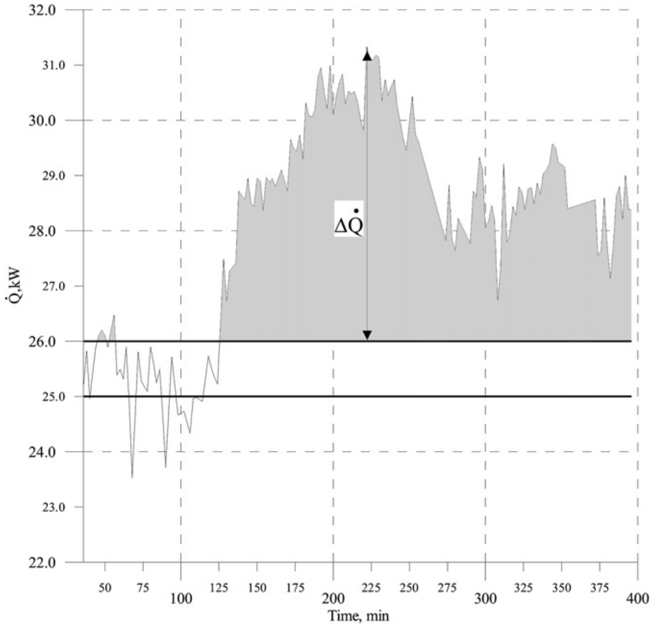


Fig. 12. Increment of the heat power of the gasifier-boiler system.

Table 4
Comparison of the results.

Fuel	This study		DiBlasi *et al.*, [5]	Lucas *et al.*, [6], [b]
	Wood pellets		Birch wood	Wood pellets
Moisture content wt., %	7.0	7.0	5.0–6.0	8.2
Air/fuel ratio kg/kg	1.73	1.14	1.05–1.27	
Excess air ratio	0.30	0.20	0.20–0.25[a]	
Syngas composition vol, d b, %				
H_2	7.13	7.96	7.00	10.60
CO	27.47	25.53	28.60–30.00	30.00
CO_2	6.22	7.06	7.00–5.50	6.00
CH_4	1.88	1.44	1.80	3.20
C_{2+}	0.14	0.12	–	0.5
O_2	1.44	3.49	–	–
N_2	54.68	56.67	55.60–55.70[a]	41.00
LHV MJ/Nm^3	4.99	4.67	5.10–5.25[a]	6.90

[a] Calculated on the basis of data presented.

[b] Oxidizer– high temperature air, $t_{air} = 350$ °C.

4. Uncertainty analysis

Uncertainties in the measurement of temperature, air flow, fuel flow and syngas composition were determined by Eq. (1) described by Dogru et al. in [7]. Accordingly to the procedure presented in [7] and [8] total uncertainties of hot and cold gas efficiencies, the air to fuel ratio and the excess air ratio were calculated by means of experimental data by Eqs. (1) and (2).

$$\sigma_{x_i}^2 = B_{x_i}^2 + P_{x_i}^2 \tag{1}$$

$$\sigma_r^2 = \sum_{i=1}^{j} \left(\frac{\partial r}{\partial x_i}\right)^2 \cdot \sigma_{x_i}^2 \tag{2}$$

where $r = r(x_1, x_2, \ldots x_j)$, which is function of j measured variables x_i; σ_r, σ_{xi} are uncertainties of r and x_i, respectively; B_{xi}, P_{xi} *are* systematic uncertainty and random uncertainty of the variables x_i, respectively. Systematic uncertainty and random uncertainty are defined as the squares root of the sum of the uncertainties of various elemental sources.

Temperatures of the gasifier interior and syngas temperatures were measured by thermocouples (N- and K-type) with an accuracy of ±0.75% for both types of thermocouples in the range of measured temperatures. Uncertainty arising from operation was assumed ±1.0% and the total uncertainty in the temperature measurement was estimated to be ±1.25% by Eq. (1).

Air flow rate was measured by a flow meter with a full scale of 20 Nm^3/h, a least count of 0.25 Nm^3/h and specified accuracy of ±2.5%; total uncertainty of the air flow rate to the gasifier is calculated to be ±2.5% by Eq. (1).

The mass of the fuel fed into the gasifier during the test was measured by a scale and at the end of each test, unused fuel taken from the gasifier was weighted. Then the total mass of fuel was divided by the time of the test determining the biomass flow rate. Scale used in order to determine the mass of used biomass had maximum permissible error of ±3 *e*, where e is verifying unit, which for the scale used in the experiment is $e = 200$g. Total uncertainty of measuring of mass within the investigated range of mass of feedstock is ±2%.

Uncertainty of fuel flow rate is affected by the uncertainty of the determining amount of fuel and uncertainty of the timer which was assumed ±1.5%. Accordingly to Eq. (1), the total uncertainty of the fuel flow is equal to ±2.5%.

Air to fuel ratio was calculated as air flow rate divided by fuel flow. Consequently, the total uncertainty of this variable is affected by uncertainties arisen from determining these two mentioned

Table 5
Uncertainties of variables.

Variable	Uncertainty %
Temperature	±1.25
Air flow	±2.50
Fuel flow	±2.50
Air/fuel ratio	±3.53
λ	±3.53
Syngas composition	±5.59
LHV of syngas	±5.59
CGE	±8.40
HGE	±7.87

variables. On the basis of Eq. (2) total uncertainty of the air to fuel ratio is equal to ± 3.53%.

Excess air ratio is calculated by means of two independent variables (air flow rate, fuel flow rate) and minimal theoretical amount of air which is needed for complete combustion (variable calculated on the basis of biomass composition- uncertainty of this variable is equal to 0). For that reason, uncertainty of λ is the same as for uncertainty of air to fuel ratio: ±3.53%.

Gas composition was measured by a gas chromatographer Agilent 6890N with an accuracy of ±2.5%. Due to the manual procedure of sampling and injection, enlarged uncertainty was estimated to be ±5% [8]. Thus, the total uncertainty of syngas composition and uncertainty of LHV of gas is 5.59%, estimated by Eq. (1).

Dry gas flow rate is calculated by means of nitrogen balance between the inlet and outlet of the gasifier and the total uncertainty of this variable is affected by uncertainties of the air flow rate and gas composition (nitrogen molar fraction). Thus, its uncertainty was calculated by means of Eq. (2) and is estimated to be ±5.94%.

Uncertainties of cold and hot gas efficiencies are determined accordingly to Eq. (2), associated with uncertainties of gas composition, gas flow rate and fuel flow rate and are estimated to be ±8.40% and ±7.87 respectively for cold and hot gas efficiency.

Total uncertainties estimated in the analysis are presented in Table 5.

5. Conclusions

Air biomass gasification was investigated in a small scale gasification system keeping to selected experimental conditions. Comparing theoretical and experimental investigation it may be seen that a general tendency of varying the composition of syngas is preserved. The molar fraction of CO in the syngas is higher in the case of dry fuels, while the molar fraction of CO_2 increases with the increment of moisture content in the raw fuel. Higher moisture content in the biomass affects the syngas composition significantly, decreasing the molar fractions of the combustible components and the efficiency of the process.

In the experimental part of the investigations the gasifier was efficiently and consistently operated within the range of feeding between 4.1 and 16.0 kg/h. The lower heating value of the obtained syngas was within the range of 3.84–5.47 MJ/Nm^3 being dependent mainly on the moisture content in the biomass.

There were any problems of bridging or ash sintering with neither of the investigated fuels, but oat husk pellets are not a suitable feedstock for gasification process, because of the low molar fractions of combustible components in the syngas.

Supplying syngas into the coal combustion zone in the boiler involved an increment of the heat power of the system amounting to 11–19% of the actual heat power of the boiler.

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